A Practical Introduction to Particle Physics at SNOLAB

Dr. Pierre Gorel

Students Orientation Session

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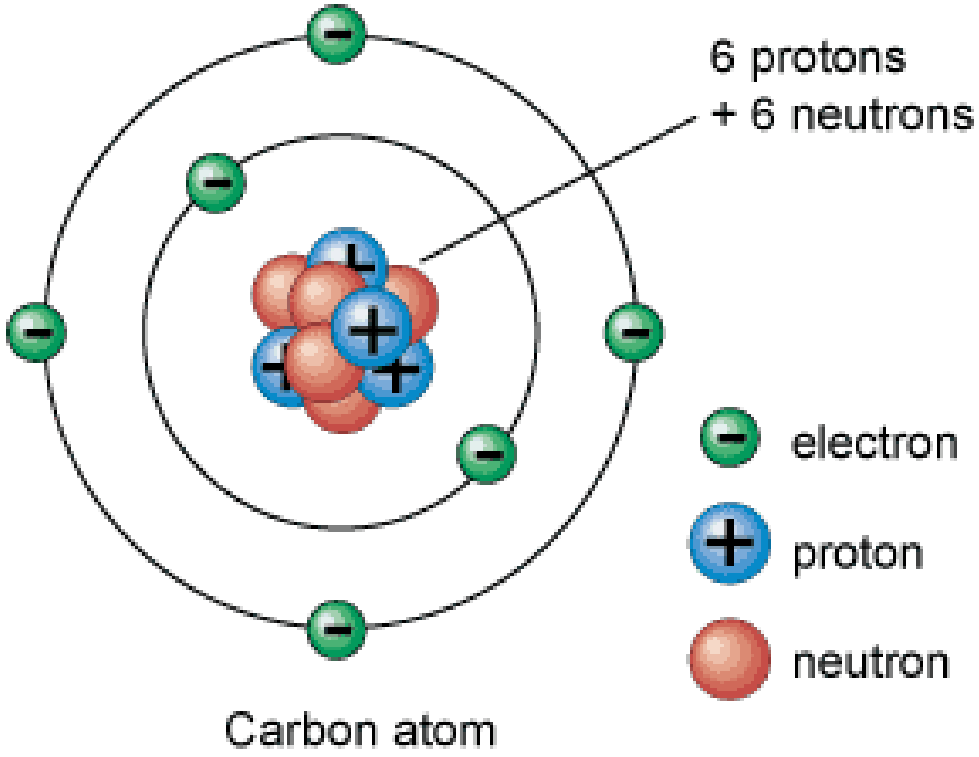
Slides adapted from Dr Tom Sonley

Atomic Theory

- Nucleus and Electrons
- Nucleus made of protons and neutrons
  - # of protons determines element
  - # of protons + neutrons determines isotope
- Electrons live in quantized energy levels (orbitals)
  - Almost always live in their lowest energy (ground) state
  - Can absorb energy to move an electron to a higher energy level or to free an electron entirely (ion)
  - 1 eV (visible light) to 10 keV (x-rays)



Molecules and Crystals

- Molecules are groups of bound atoms
  - Energy of the bound group is less than the energy of separate atoms
  - Can be configured in different ways. These configurations are quantized.
  - 1 neV (Radio Frequency) to 10 eV (visible light)
- Crystals are large groups of similar atoms in a repeating lattice
  - There are strong quantum-mechanical effects
  - Electron energy levels are grouped over the whole crystal (bands)
  - Energy gap between valence bands and conduction bands determines properties: insulator, conductor, or semi-conductor
  - For semi-conductors, band gap is around 1 eV (visible light)
  - Vibrations are also quantized (phonons)

Nucleus

- Protons and Neutrons live in quantized energy levels.
  - Almost always in the ground state
- Neutrons can change to protons via **β-** decay.
- Protons can change to neutrons via **β+** decay.
- An **α** (^{4}He nucleus) particle can escape
- A **neutron** can escape
- The new nucleus (daughter) will probably be in an **excited state**.
  - It will emit gamma rays to reach the ground state. 1 keV (x-rays) to 5 MeV (gamma rays)

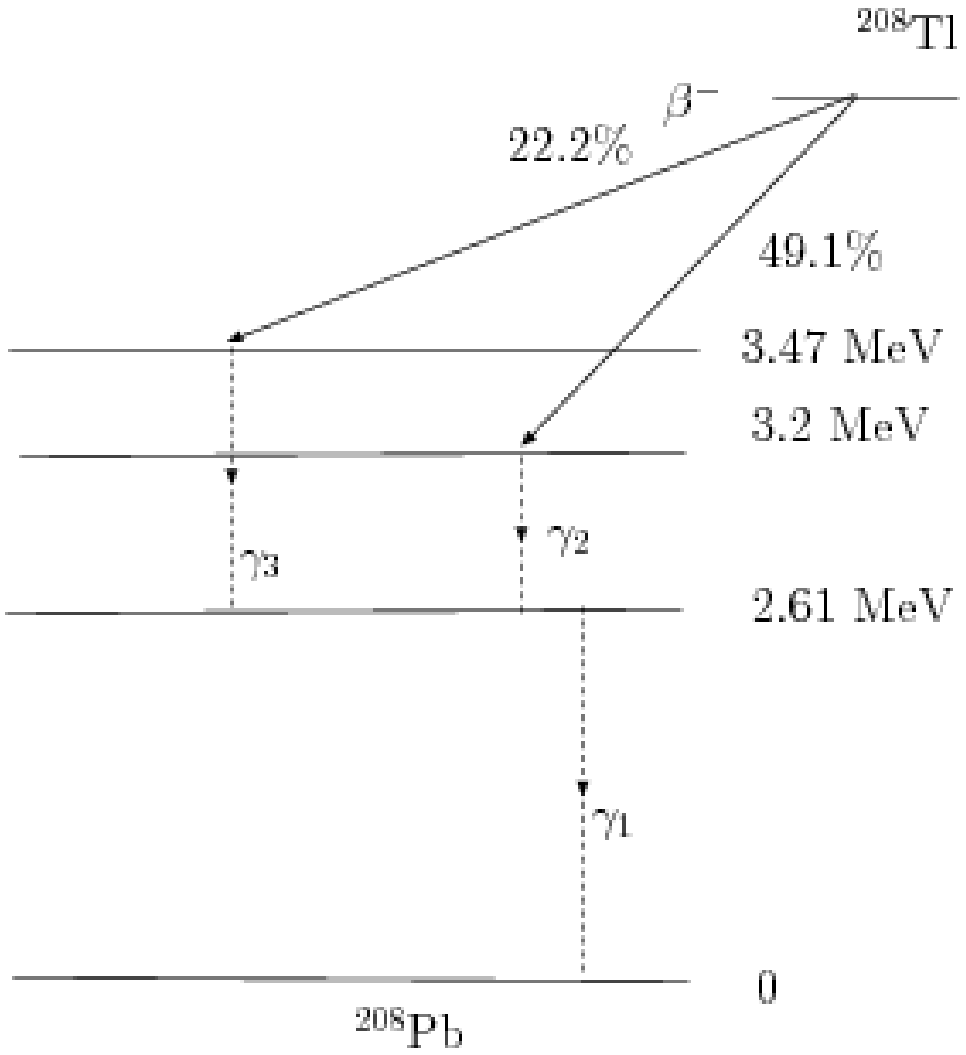
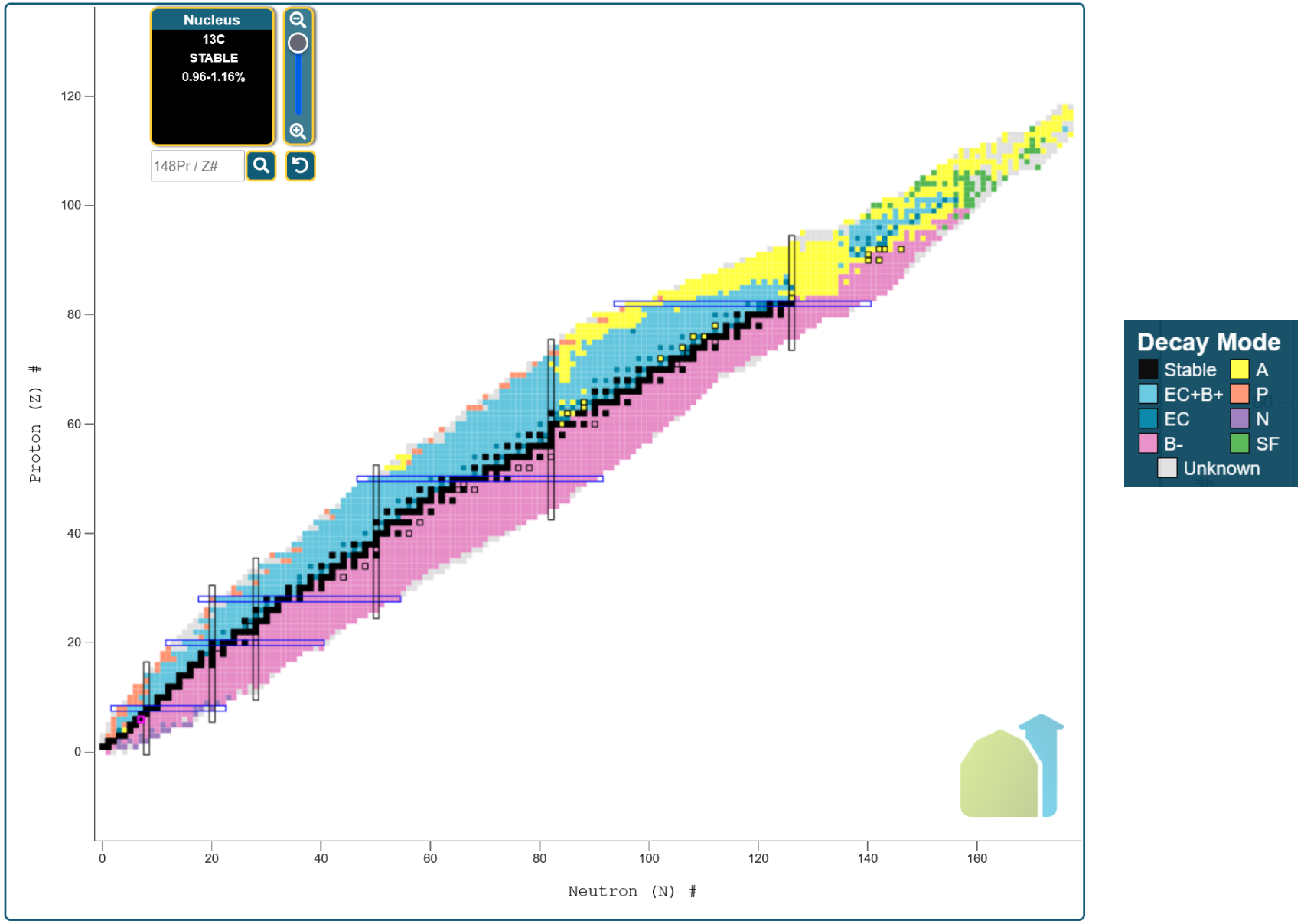
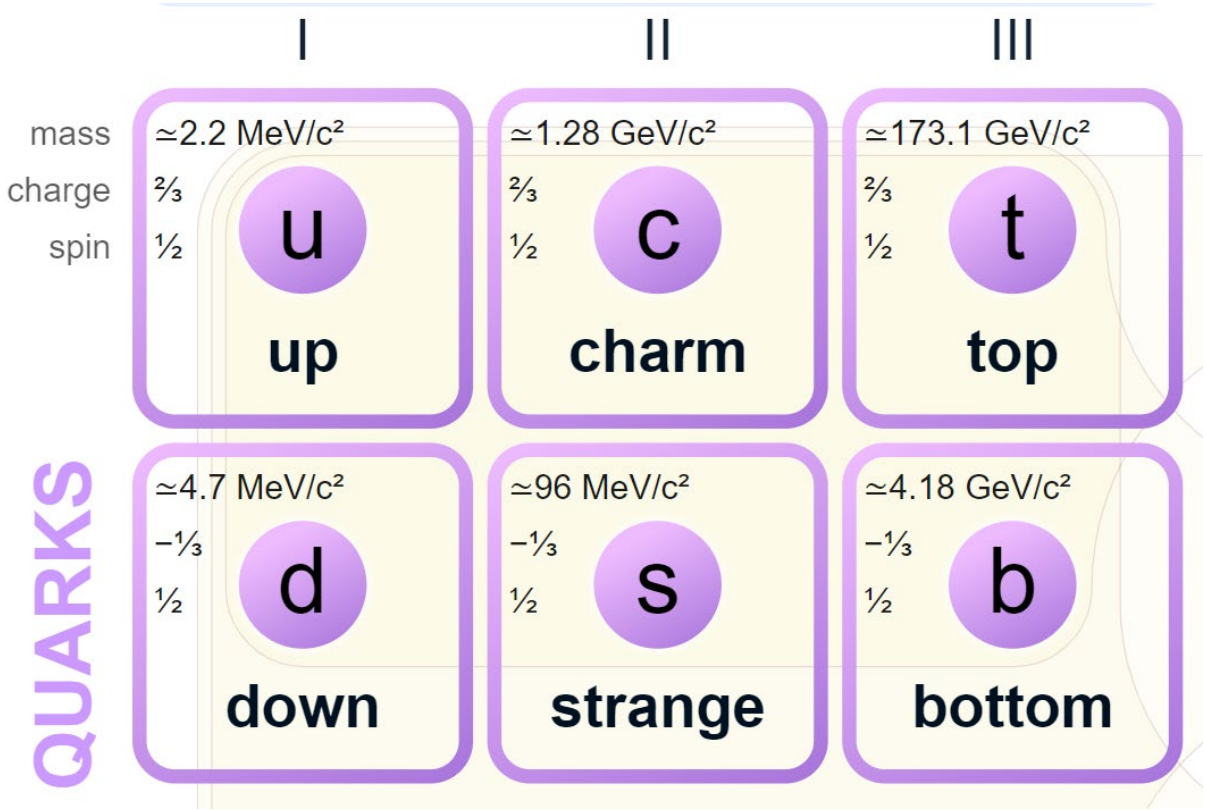


Chart of Nucleides (https://www.nndc.bnl.gov/)



Quarks and Hadrons

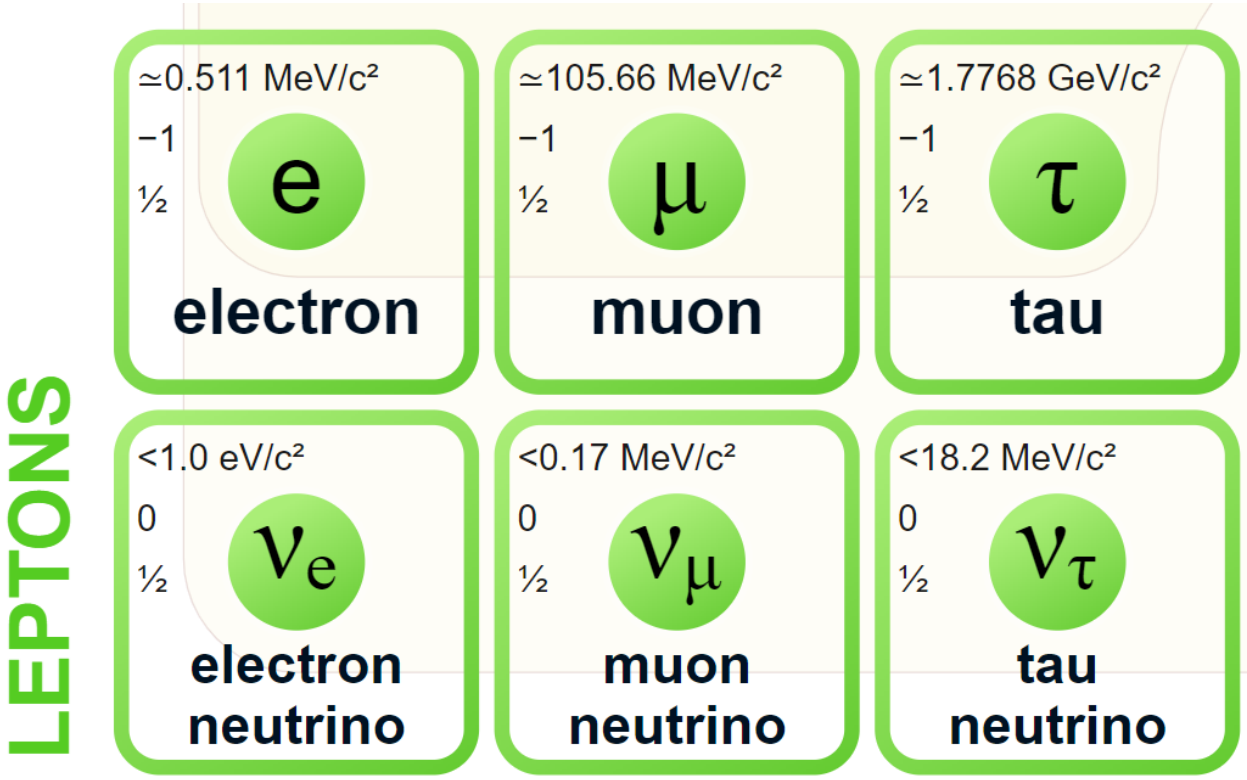
- **Baryons** are groups of 3 quarks
  - Proton = uud 938 MeV
  - Neutron = udd 940 MeV
- **Mesons** are groups of 2 quarks
  - $\pi^+ = u\bar{d}$ 140 keV
  - $\pi^0 = (u\bar{u} - d\bar{d})/\sqrt{2}$ 135 keV
  - $\pi^- = \bar{u}d$ 140 keV
- Single quarks are **never observed**



- Quarks interact through the **Strong, Electromagnetic, and Weak** forces

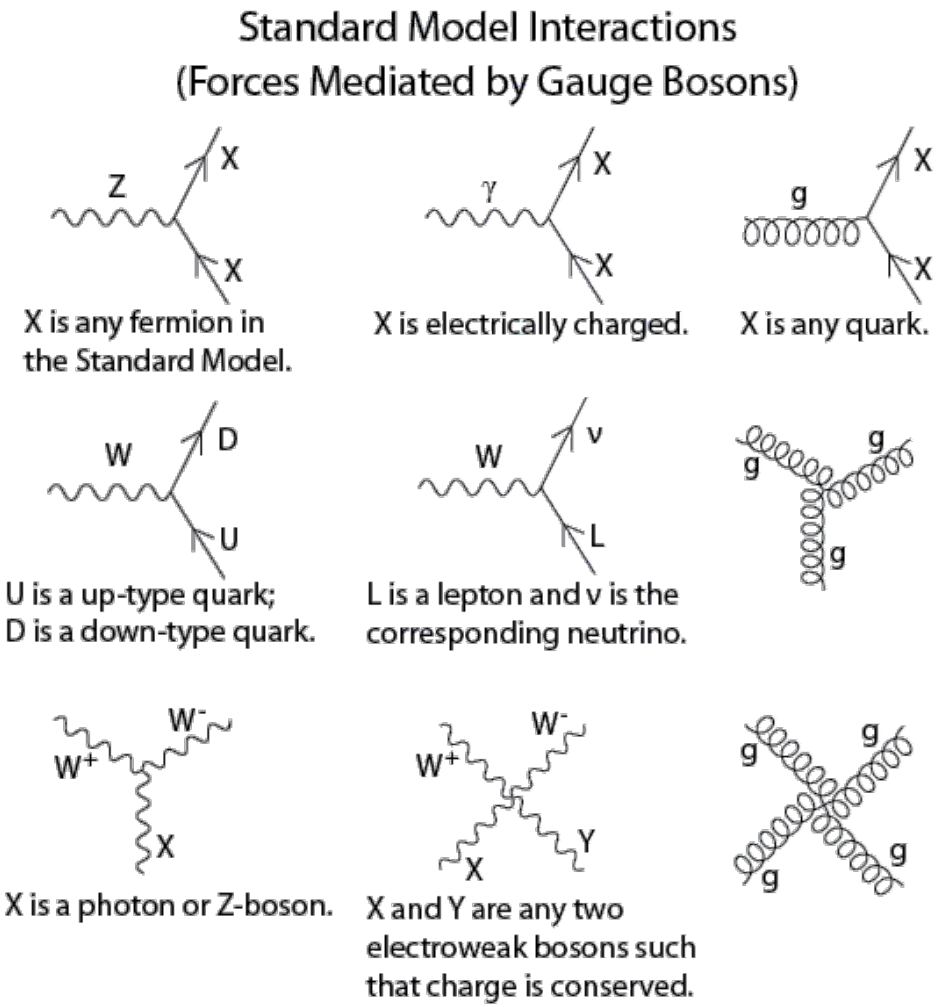
Leptons

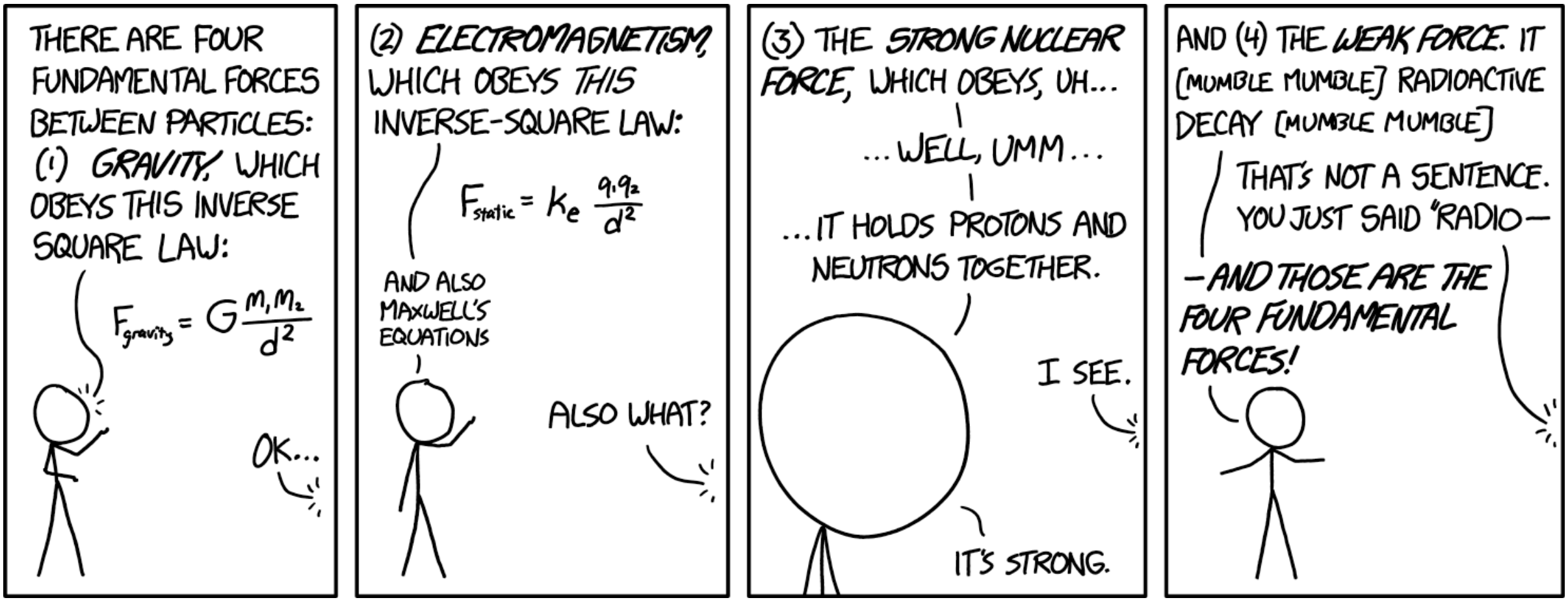
- **Electrons, muons, and taus** interact through the **Electromagnetic and Weak forces**
- **Neutrinos** interact only through the **Weak force**
  - Primarily created in beta decay, pion decay, muon decay and fusion
  - Extremely difficult to detect
  - Most abundant particle in the universe
  - All observed neutrinos are left-handed



Particle Interactions

- All interactions are through a **force carrier**:
  - **Gluon** for Strong force
  - **Photon** for Electromagnetic Force
  - **$W^{\pm}$**, or **Z** for the Weak Interaction
- All interactions can be represented as a Feynman Diagram
- Relativistic Energy and Momentum must be conserved at the start and end.
  - But can be violated a bit in the middle
- Other quantum numbers must be conserved (parity, chirality, etc.) leading to "forbidden decays"

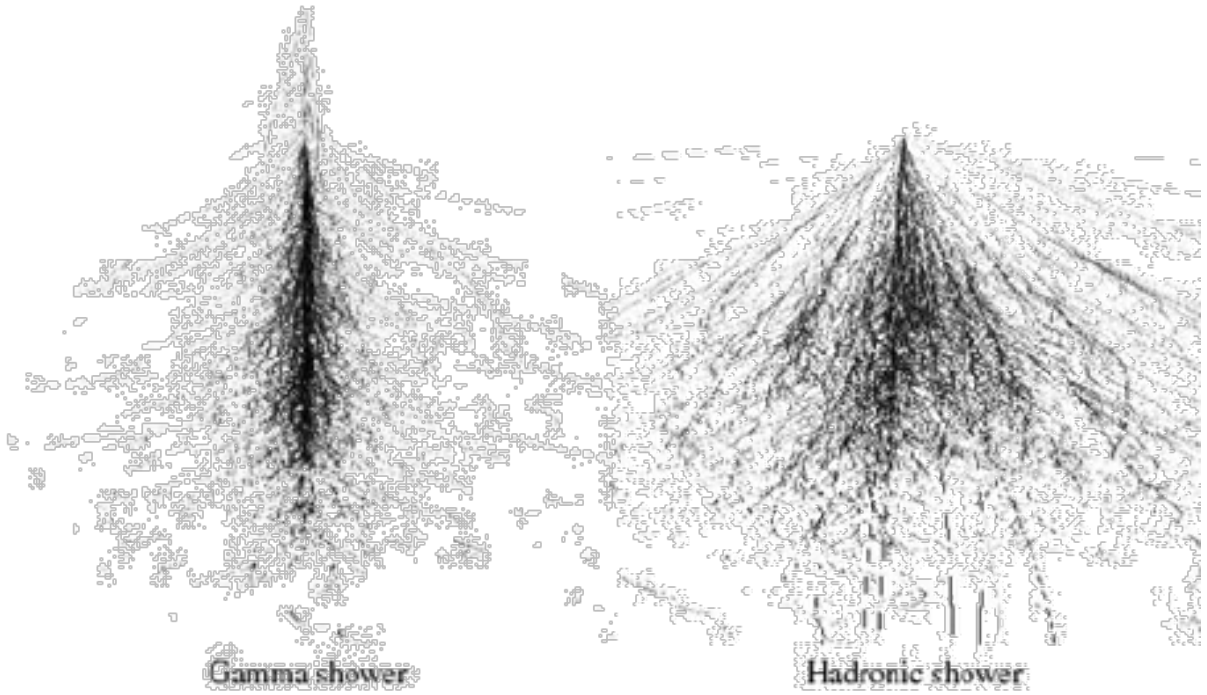




https://xkcd.com/1489/

Strong Interaction

- Mediated by Gluons and Quantum Chromodynamics (QCD)
- Holds baryons and mesons together
- 2^{nd}-order effects hold nuclei together (virtual pion exchange)
- Gluons interact with each other -> extremely complicated calculations
- In accelerators, strong interactions produce “hadronic showers” aka “jets”
  - Tons of pions, leptons, and photons from very fast decays



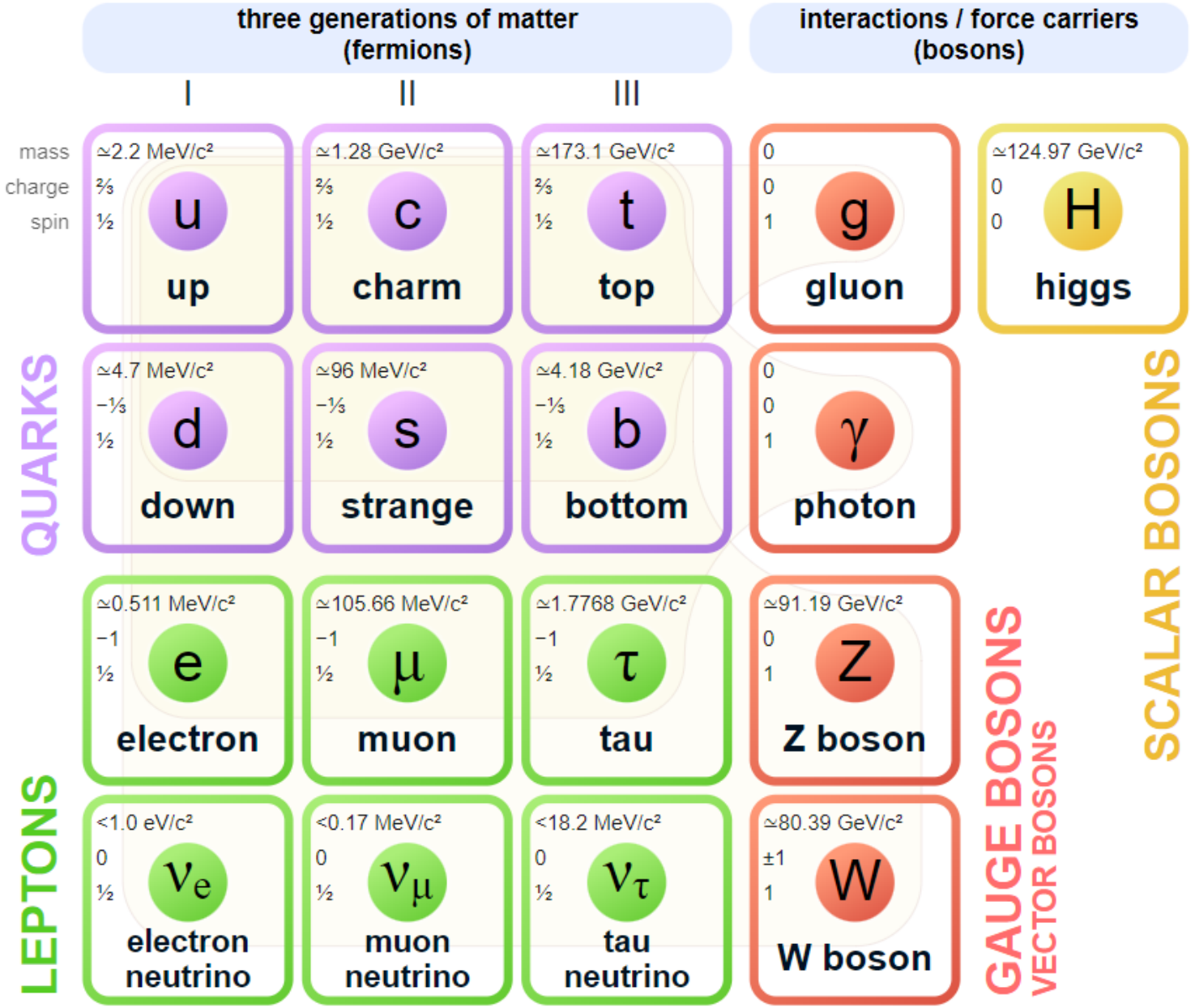
Weak Interaction

- Mediated by W (80 GeV) and Z (91 GeV) bosons
- Outside of accelerators, much less common than Strong or Electromagnetic interactions
  - Only seen when other interactions are not possible
- Only interaction that can change a “u” quark into a “d” quark,
  - Can also cross quark generations (c quark into d quark).
- Only interaction that produces neutrinos and lets them interact with matter.

Electromagnetic Interactions

- Mediated by the photon.
- Most common particle interaction.
- Let’s us detect particles.
  - Photons:
    - Compton Scattering
    - Photoelectric Effect
    - Pair Production
  - Massive Charged Particles: Bethe-Bloch formula
  - Electrons - Low Energy: Ionization
  - Electrons - High Energy: Electromagnetic Showers
    - Bremsstrahlung, Pair Production
  - All fast charged particles: Cherenkov Radiation

Standard Model of Elementary Particles



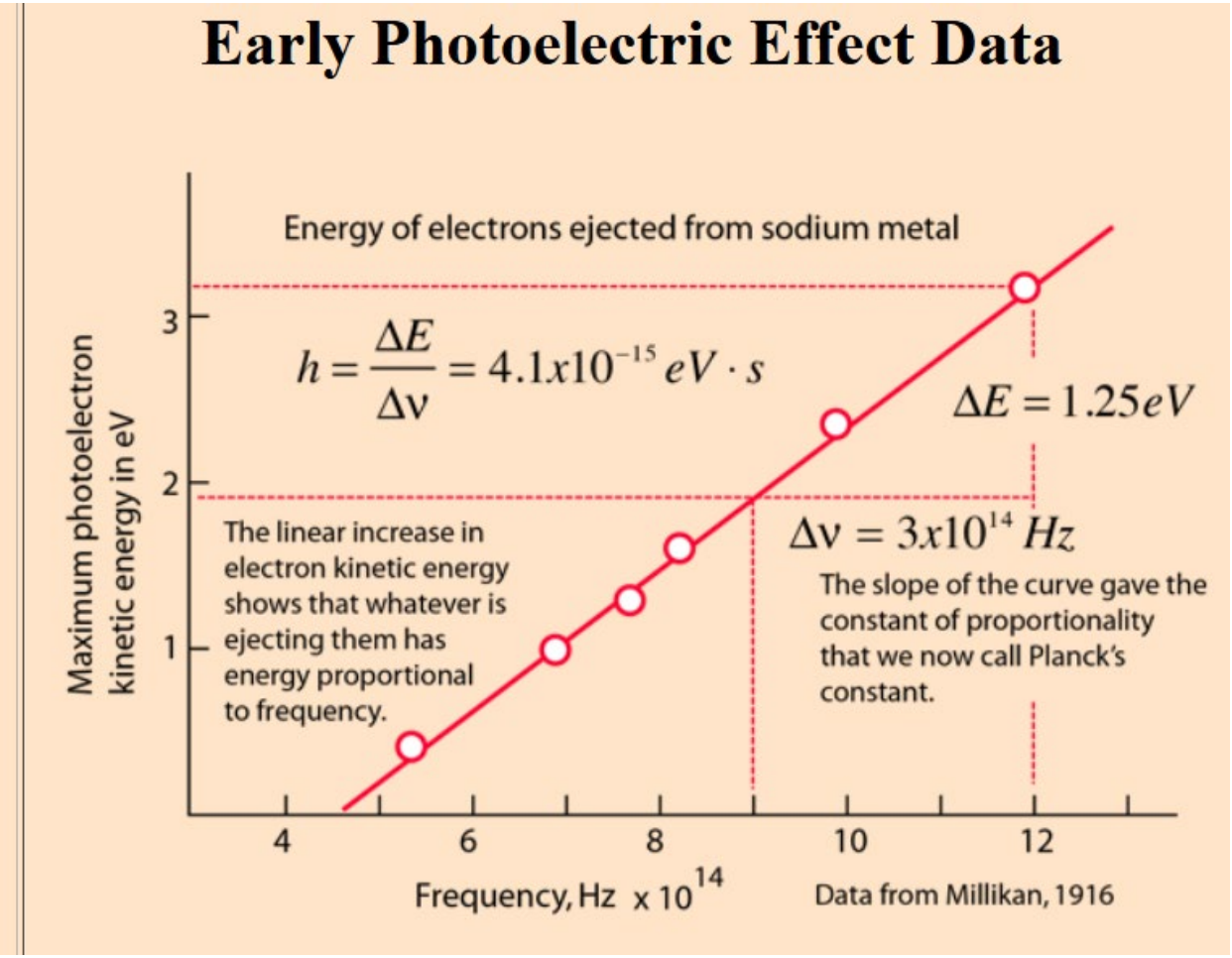
Interaction particles and matter

Most likely involving:

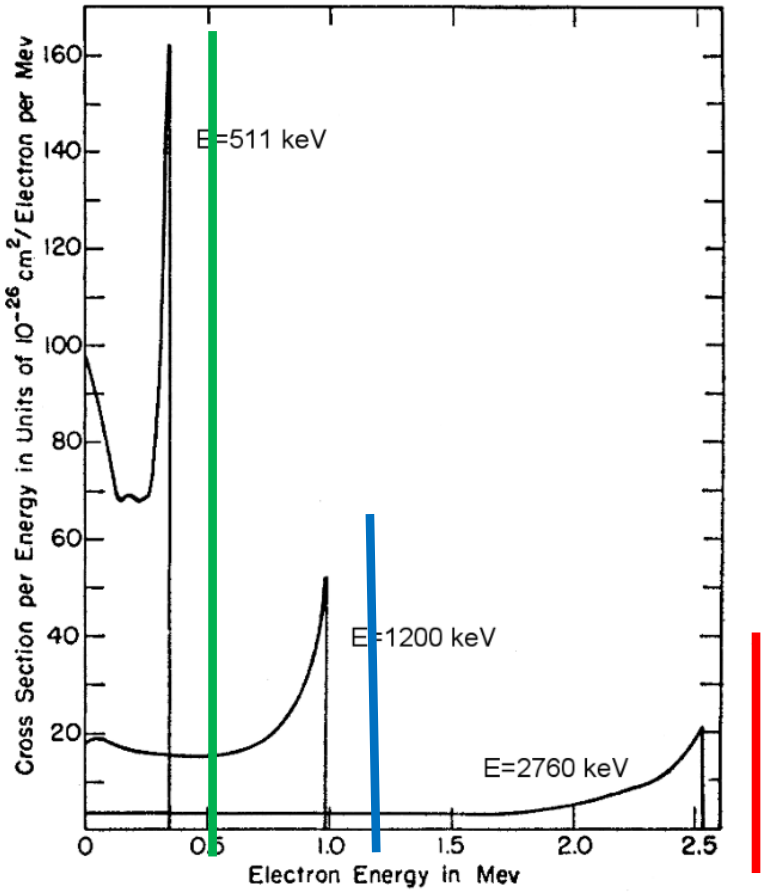
- Photons (gamma rays, X-ray)
- Charged particles (electrons, muons, alphas)

Photoelectric Effect

- Photon is absorbed by atom, electron is released
- Electron has energy equal to photon energy – atomic binding energy



Compton Scattering



Electron Energy

- Photon bounces off an electron like billiard balls
- Exit direction of photon determines energy of photon and electron.

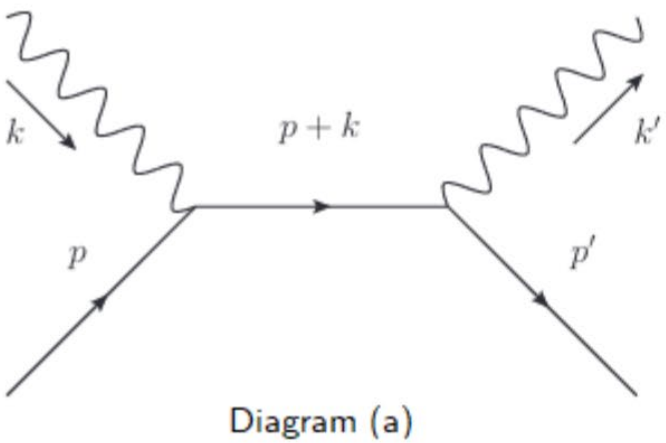


Diagram (a)

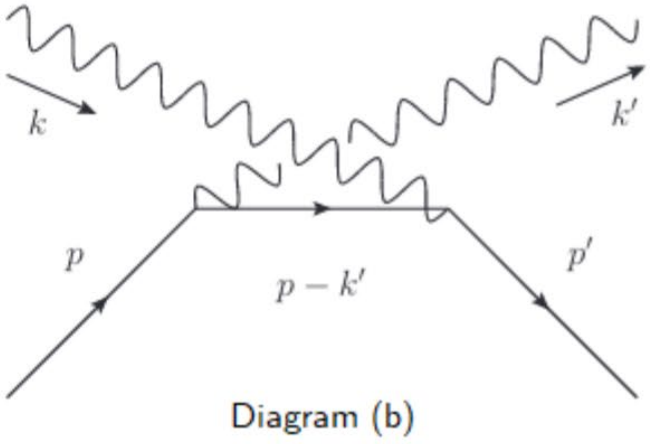
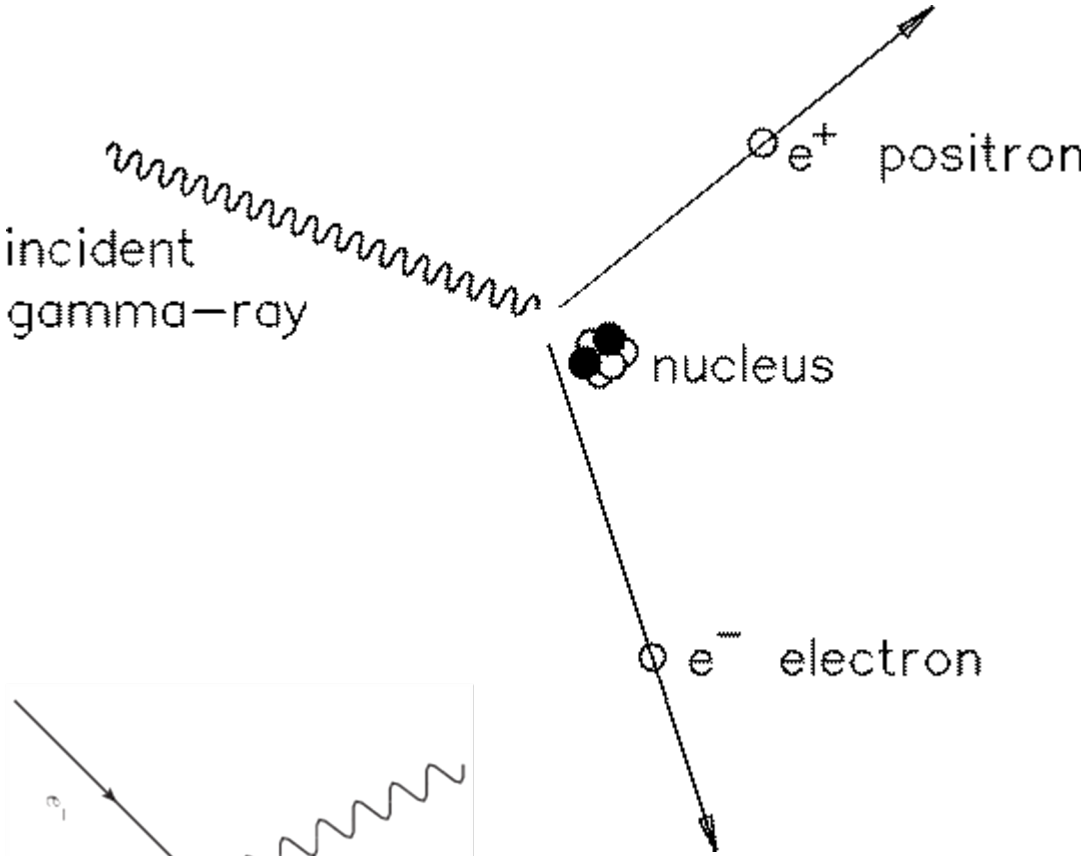


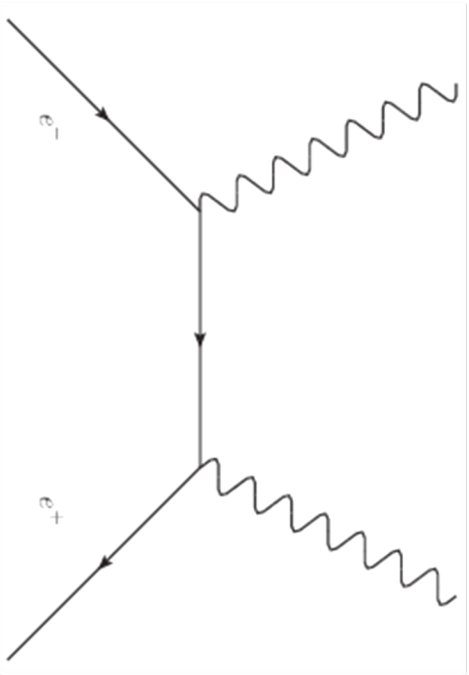
Diagram (b)

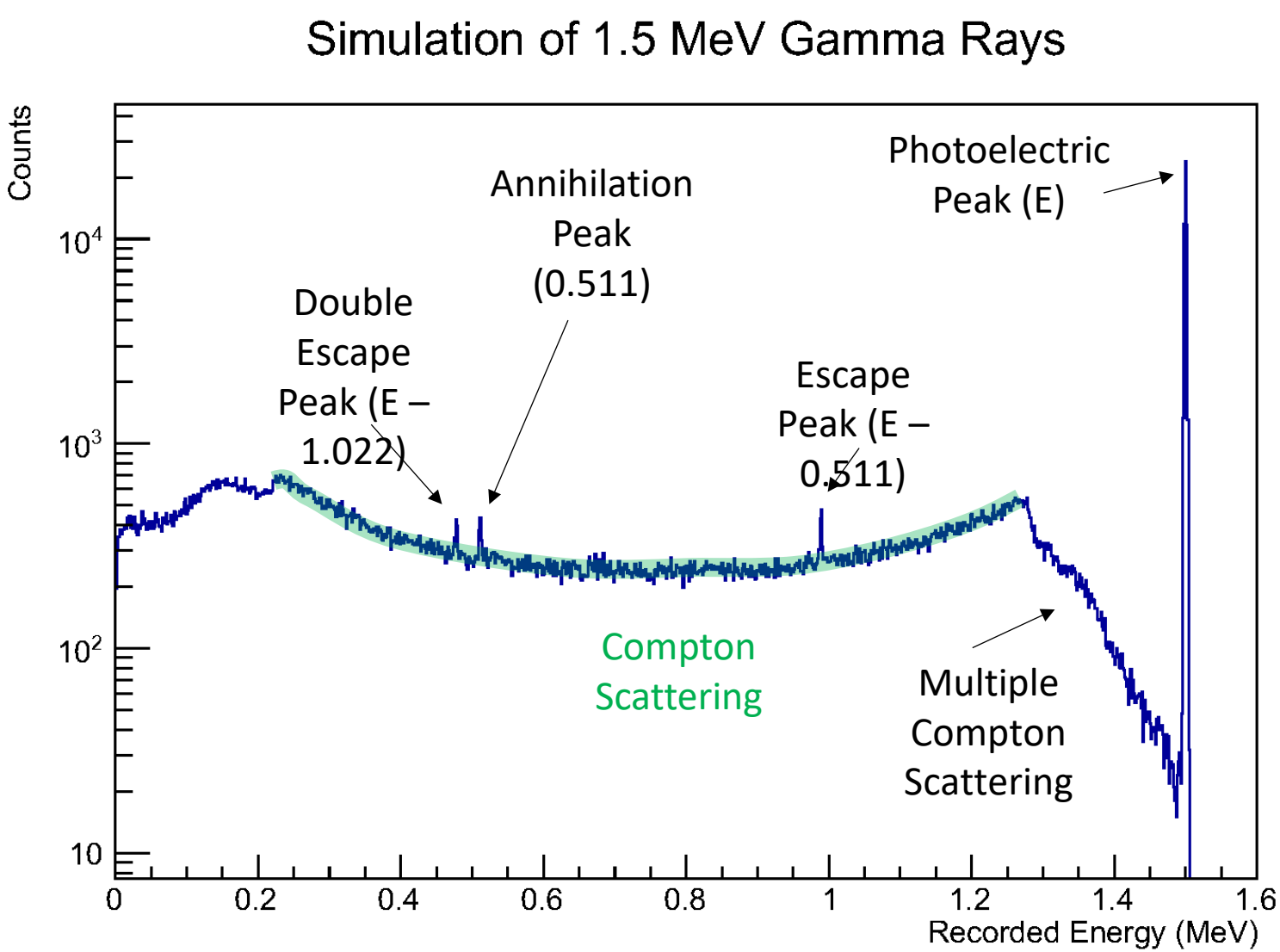
Pair Production

- Incident photon converts into an electron-positron pair
- Only possible in the presence of matter to conserve momentum
- Only possible if gamma ray energy is > 1 MeV



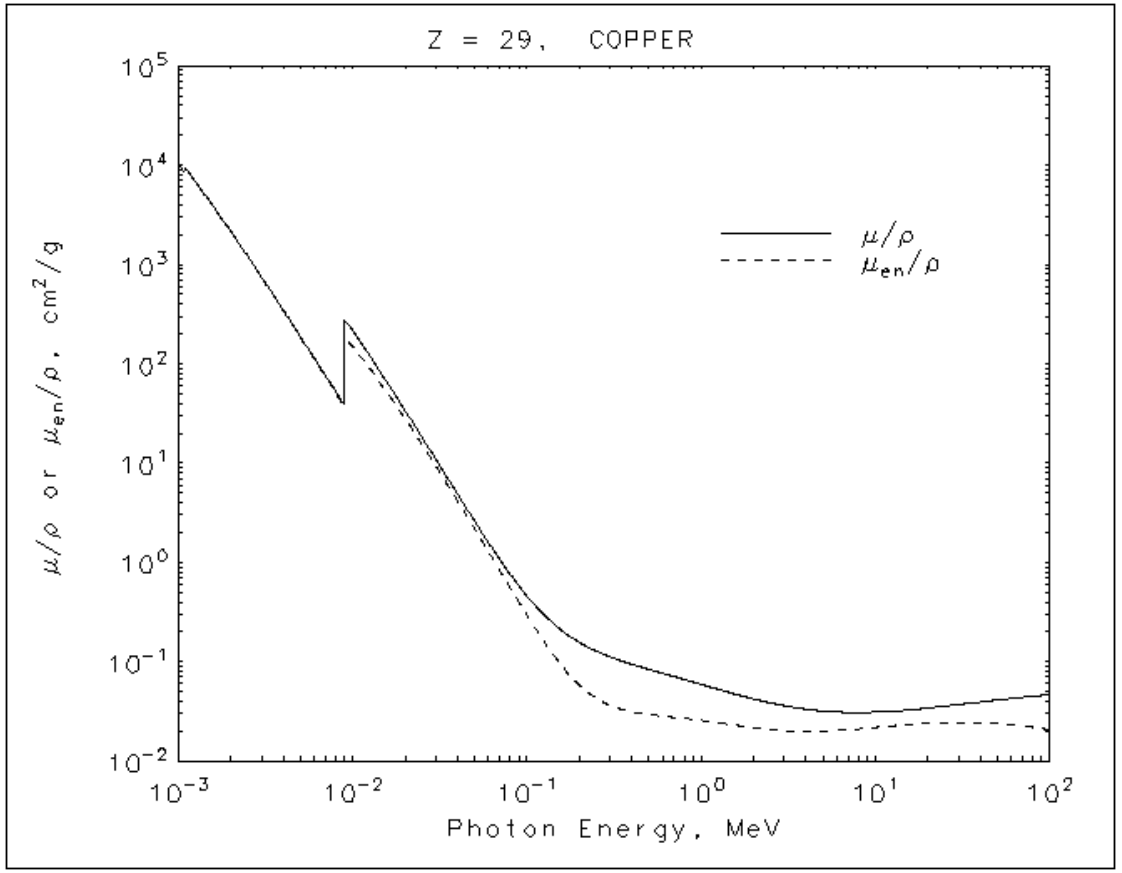
- Positron will quickly annihilate with an electron, producing 2 gamma rays with 511 keV each



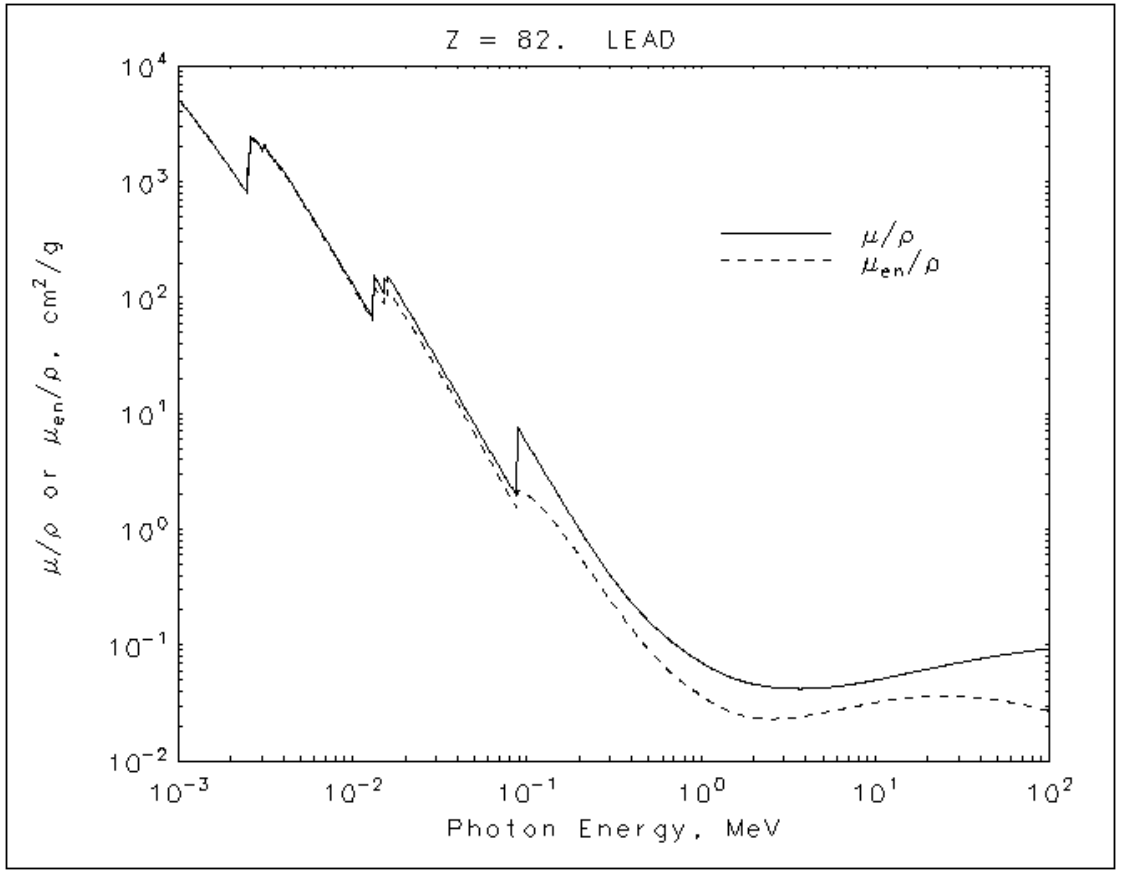


Line widths are usually set by the resolution of the detector.
Germanium detectors have resolutions of 1 to 3 keV.

Photon Attenuation

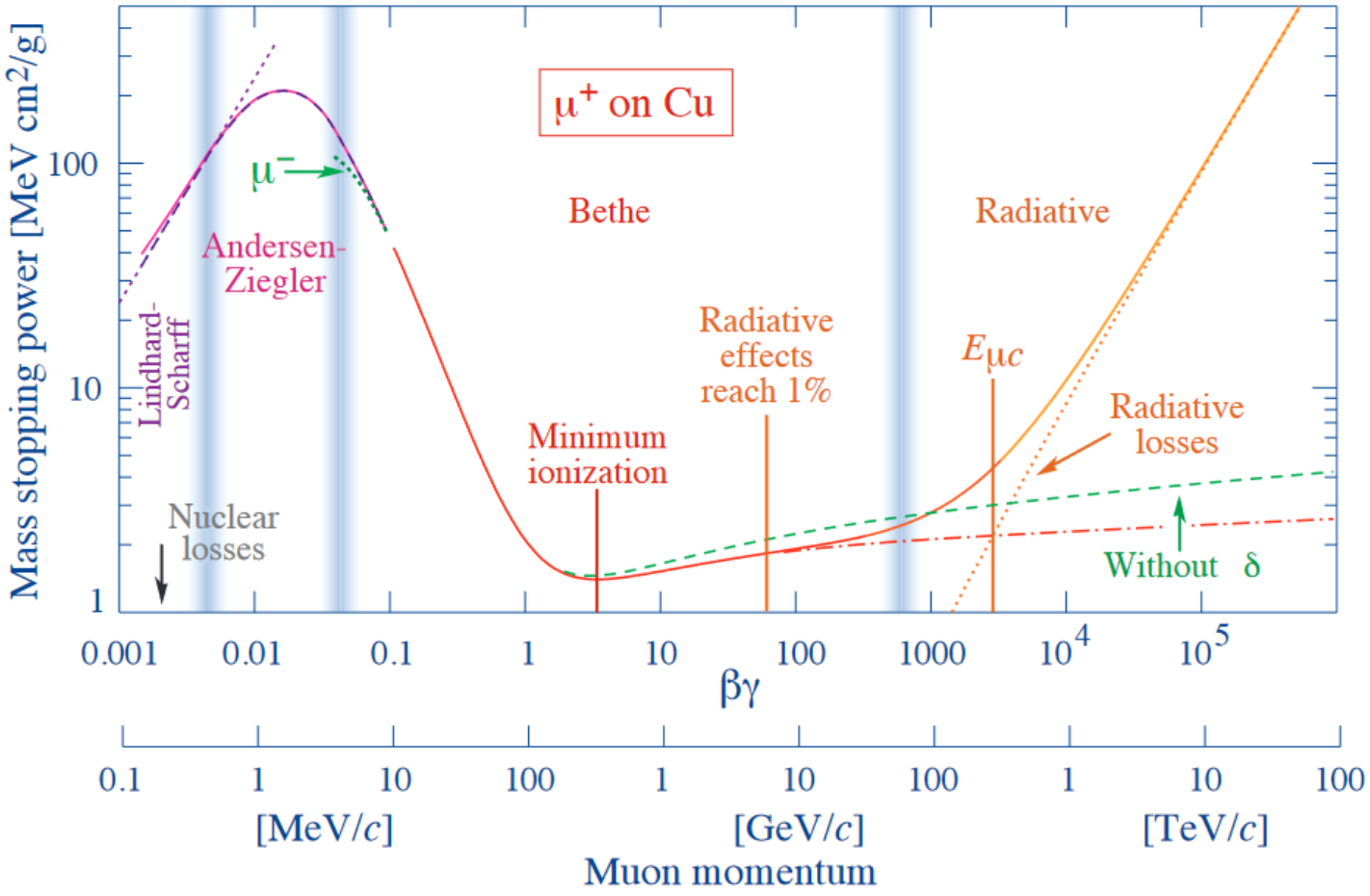


At 1 MeV, gamma rays are attenuated by 1/e at 1.9 cm in copper.

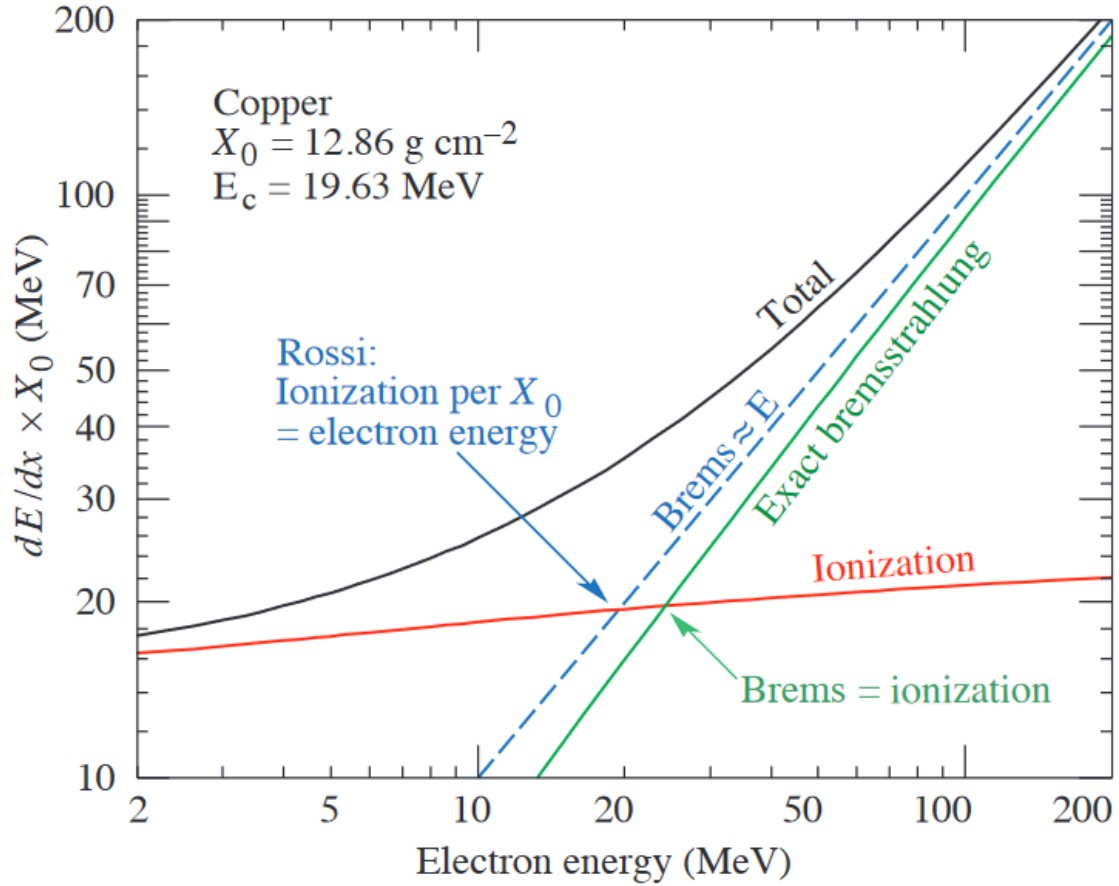


At 1 MeV, gamma rays are attenuated by 1/e at 1.2 cm in lead.

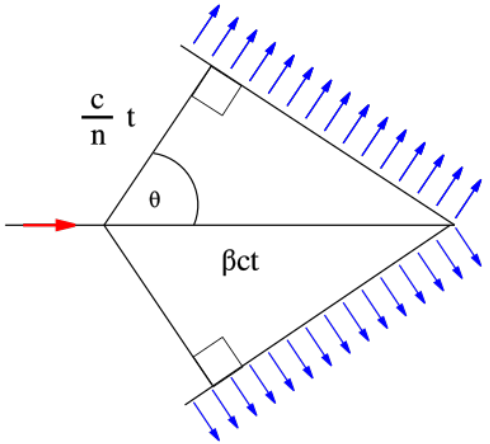
Heavy Charged Particles: Bethe-Bloch Formula



Electrons


Copper
X_0 = 12.86 g cm^{-2}
E_c = 19.63 MeV
Rossi:
Ionization per X_0
= electron energy
Total
Brems ≈ E
Exact bremsstrahlung
Ionization
Brems = ionization
$dE/dx \times X_0$ (MeV)
Electron energy (MeV)
200
100
70
50
40
30
20
10
2
5
10
20
50
100
200

Cherenkov Radiation

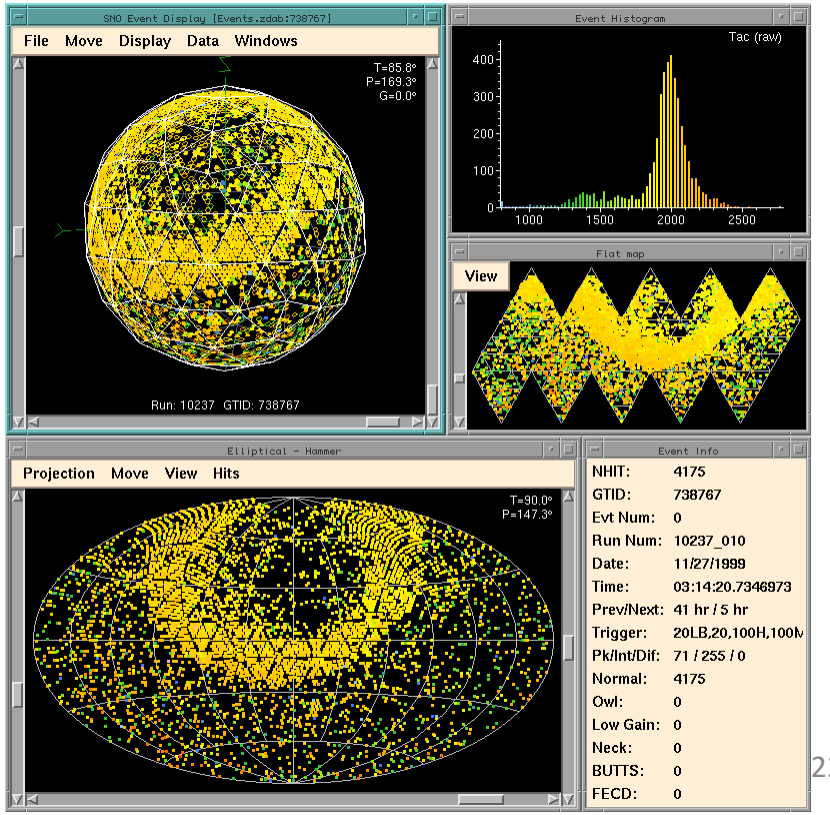


$$\frac{c}{n} \leq v_p < c$$

$$\beta = \frac{v_p}{c}$$

➔ $\cos\theta = \frac{1}{n\beta}$

- "Sonic Boom" of light
- Particle must be traveling faster than the speed of light in the medium
- Light is emitted only at angle θ



An upward going contained event (SNO)

Cherenkov Radiation

- “Sonic Boom” of light
- Particle must be traveling faster than the speed of light in the medium
- Light is emitted only at angle θ_c
- Extremely weak source of light

Common Interactions at SNOLAB

- Comic Ray muons
  - Produced in the atmosphere by cosmic rays (extremely energetic protons)
  - Travel through the detectors
  - Deposit tons of energy
  - Can break up nuclei (spallation) which releases neutrons, and can activate other materials
- Alpha Decays
  - Nuclear decay that releases a helium-4 nucleus
  - Very energetic
  - Very short-ranged (mm in material)
- Beta Decays
  - Nuclear decay that releases an electron or positron (and neutrino)
  - Range of around 10 mm
- Gamma Decays
  - De-excitation of a nucleus after another decay
  - Highly penetrating
- Neutrons
  - Very rarely released
    - fission decays
    - spallation
    - alpha particle interactions
  - Highly penetrating
  - Detected as either nuclear recoil or capture on another nucleus